

Another solution to the puzzle of the direct photon elliptic flow

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The observed large elliptic flow of direct photons is a puzzle in relativistic heavy ion physics. Our previous work provided a possibility to this puzzle with the delayed formation of the quark gluon plasma (QGP) in relativistic heavy ion collisions. In this work, we got the measured transverse momentum spectra, elliptic flow v_2 and triangular flow v_3 of direct photons from Au+Au collisions at the Relativistic Heavy Ion Collider (RHIC) energy $\sqrt{s_{NN}} = 200$ GeV with all centrality classes explained at the same time without any additional parameter to EPOS3, a hydrodynamic model which can successfully reproduce hadronic data such as rapidity distributions, transverse momenta, elliptic flows and triangular flows from various collision systems. The key point is that, EPOS3 has an initial space eccentricity similar to other models, however, a stronger radial flow and a weaker momentum eccentricity made a good description to the flows of both hadrons and direct photons. The created QGP matter seems discrete than a soup.

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I. INTRODUCTION

As a golden probe, direct photons have been highly expected to reveal the properties of the hot dense matter formed in relativistic heavy ion collisions. The observed large elliptic flow of direct photons [1, 2] has attracted a lot of attention [3–7]. It is indeed hard to understand that photons and hadrons carry the same magnitude of elliptic flows, because most of photons are produced at a so early stage of the heavy ion collisions that the flow is not well developed to drive an anisotropic emission. Thus people considered some additional sources of photons or pre-development of flow to explain this puzzle. However, the consideration of additional photon source, ie, related to the magnetic field, is difficult to survive the latest data such as the triangular flow of direct photons. The pre-development of flow is in fact equivalent to the delayed formation of QGP[8], because the material component and structure during the pre-development of flow should be explained. A gluon-rich system with less photon emission before QGP formation is an appropriate choice.

One of the main goals of relativistic heavy ion collisions is to study the properties of QGP which is believed to have existed in the early stage of our universe. The gluon-rich system before QGP formation in relativistic heavy ion collisions is hot and energetic (massive in a big system) but not as bright as expected. The QGP matter provides a high temperature blackbody-like radiation, while the gluon-rich system is much fainter or even dark according to the quark fugacity. Thus it may offer a good candidate to dark matter and dark energy [9] with further study of the extreme condition for its existence. To be serious, one should investigate more systematically in the lab for the conclusion of the sky, for example, checking other possibilities to this direct photon puzzle.

Unexpectedly we do find another solution with EPOS3.

The paper is organized as following. In section 2 will show the results of direct photons and charged hadrons. A surprising reproduction of direct photon results such as transverse momentum spectra, elliptic flow v_2 and triangular flow v_3 ! While hadron data are also explained at the same time. To understand what builds up such a big elliptic flow of photons, we investigated the EPOS3 model in section 3. Special attention has been paid to the space-time evolution of the collision system. To make sense, a comparison of the results is made with a Glauber-initial hydro model [10]. As long as the second order eccentricity and elliptic flow concerned, [10] is a good bridge to connect most of the currently popular hydro models. Discussion and conclusion are made in section 4.

II. RESULTS OF DIRECT PHOTONS AND CHARGED HADRONS

We started with showing the direct photon results from EPOS3, such as the transverse momentum spectra, elliptic flow and triangular flow. In Fig. 1, the calculated transverse momentum spectra of direct photons (full solid lines) from AuAu collisions at 0-20%(left) and 20-40%(left) agree reasonably well with the PHENIX data (full dots). Two contributions to direct photons are considered in our calculation. One is prompt photons, shown as dashed-dotted lines, are calculated until next to the leading order[8]. Thermal photons, shown as dashed lines, are calculated as

$$dN^{\text{th}}/dyd^2p_t = \int d^4x \Gamma(T, u). \quad (1)$$

The time integration is from hydro initial time $\tau_0 = 0.35$ fm/c till energy density 0.08 GeV/fm³ for each space point, with full AMY rate [11] in QGP phase and TRG rate [12] in hadronic phase. The temperature T and flow

velocity u at each space point x is provided by EPOS3, which will be explained in next section.

In Fig. 2, the calculated elliptic flow v_2 (upper panels) and triangular flow v_3 (lower panels) of photons (solid lines: direct photons) from AuAu collisions at 200GeV with centrality 0-20%, 20-40% and 40-60% (from left to right) are compared with PHENIX data[1] (Full dots). A quite good agreement of the elliptic flow v_2 of direct photons at all centralities between data points and calculated curves are evidently shown. The calculated result of triangular flow v_3 is not as good v_2 , but still within the error bar of data points for all centralities.

The flow of direct photons is calculated as

$$v_n = v_n^{\text{th}} * N^{\text{th}} / (N^{\text{th}} + N^{\text{pr}}) \quad (2)$$

where N^{th} and N^{pr} stands for the number of thermal photons and prompt in each given p_t bin, respectively. The prompt photons are assumed to carry zero flow. v_n^{th} is the n th flow of thermal photons, shown as dashed lines in Fig. 2, are calculated as

$$v_n = \cos n(\phi - \Psi_n), \quad (3)$$

where the event plane Ψ_n satisfies

$$\Psi_n = \frac{1}{n} \arctan \frac{\langle \sin n\phi \rangle}{\langle \cos n\phi \rangle}. \quad (4)$$

Here $\langle \dots \rangle$ stands for an average over the azimuthal angles of the produced photons in the momentum space.

With a nice reproduction of the transverse spectra, v_2 and v_3 of direct photons at the same time, a natural question is, how well is the hydro evolution constrained by hadron data? The hydro evolution is provided by EPOS3. Its long history makes an excellent description to the rapidity distribution and transverse momentum spectrum of not only charged hadrons but also identified hadrons. We show the relevant results in Fig. 3, where the elliptic flow v_2 (left panels) and triangular flow v_3 (right panels) of charged hadron from AuAu collisions at 200 GeV with centrality 10-20% (upper panel) and 40-50% (lower panel) are compared with experimental data[14] (full dots). Here the different types of curves stand for different approaches to obtain hadrons flow, ie, cumulant approach with two particle pseudo-rapidity difference $\Delta\eta > 1$ (red solid lines), cumulant approach with $\Delta\eta > 2$ (green dashed lines), event plane approach (black thin dashed dotted lines), scalar product approach (blue thin dashed lines), participant plane approach (yellow dashed dotted lines). The measured elliptic flow and triangular flow of charged hadrons are reasonably reproduced by EPOS3.

III. TIME EVOLUTION OF SPACE/MOMENTUM ECCENTRICITY AND PARTICLE PRODUCTION IN EPOS3

Now we investigate what builds up such a big elliptic flow of direct photons in EPOS3. As explained in

[16], EPOS3 is an event generator based on a 3+1D viscous hydrodynamic evolution starting from flux tube initial conditions [17], which are generated in the Gribov-Regge multiple scattering framework [18]. An individual scattering is referred to as Pomeron, identified with a parton ladder, eventually showing up as flux tubes (or strings). Each parton ladder has a certain probability to be a pQCD hard process, plus initial and final state linear parton emission. In any case, they constitute eventually both bulk matter, also referred to as "core" (which thermalizes, flows, and finally hadronizes) and jets (also referred to as "corona"), according to some criteria based on the energy of the string segments and the local string density. The spectator partons sitting at leading rapidity region also belong to corona.

Concerning the core, we use a 3+1D viscous hydrodynamic approach, employing a realistic equation of state, compatible with lQCD results. From the fluid dynamical expansion of the core, we get the complete space-time information, i.e. the collective velocity $\vec{v}(x)$ (which define the local rest frame (LRF) at each point x) and the temperature $T(x)$ of matter for a given space-time x , starting from some initial proper time τ_0 . With the expansion in volume, the system gets cold to $T_H = 168$ MeV. The usual Cooper-Frye freeze-out procedure is employed to convert the fluid into particles. Then hadronic cascade [19].

The detailed formula of photon calculation has been presented above. Cold collisions make prompt photons when the projectile and target meet each other. Thermal photons are produced from the "core" during its expansion and cooling. The treatment of macroscopic variables in order to make thermal photon calculation is quite similar to the sister paper on dileptons [20].

To get a good understand of the system evolution in EPOS3, we'd better compare with other models. Our previously used Hirano's (3+1)dimensional hydrodynamic model [10] can serve as a good bridge. It reproduces successfully the rapidity distribution, transverse momentum spectra and elliptic flows of charged hadrons [10] and provides a successful explanation of the transverse momentum spectra of direct photons [21]. But similar to other groups, it offers a lower elliptic flow of direct photons [22]. Hirano's hydro model is not a state-of-art in the sense that no viscosity and not simulated event-by-event. But viscosity modifies very little the photon elliptic flow. And photons from event-by-event hydrodynamics and Hirano's are compared in [8]. For example, the average of many event-by-event initial conditions make also an almond-shape in the transverse space, the same as Glauber initial condition of Hirano model. The momentum spectrum and elliptic flow of direct photons from both cases are quite close to each other.

In the following comparison, the same notation has been used from Fig. 4, 5 and 7, where thin lines are 50 random EPOS3 events to illustrate event fluctuation, the thick lines are the average of 2000 EPOS3 events and stars are the results of [10], noted as "hirano".

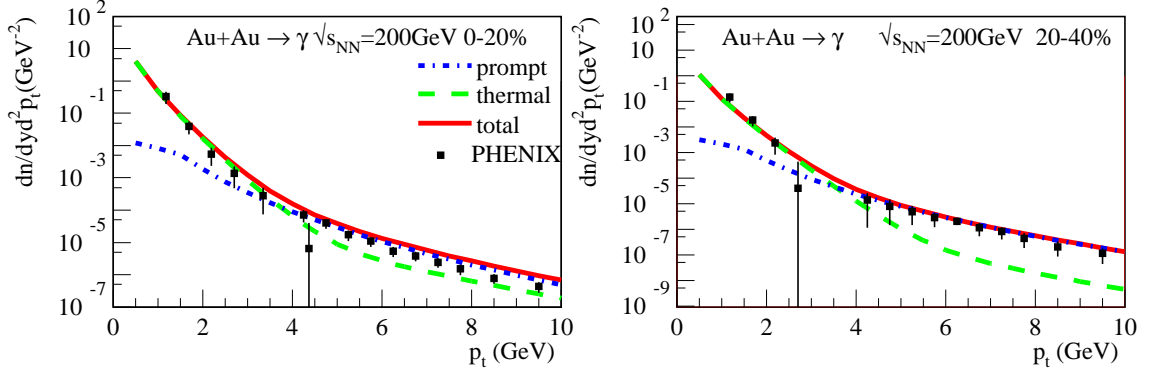


Figure 1: (Color Online) The transverse momentum spectra of direct photons (solid lines), prompt photons (dotted dashed lines) and thermal photons (dashed lines) from AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV for centrality 0-20% (left panel) and 20-40% (right panel). Data points of direct photons from PHENIX [13].

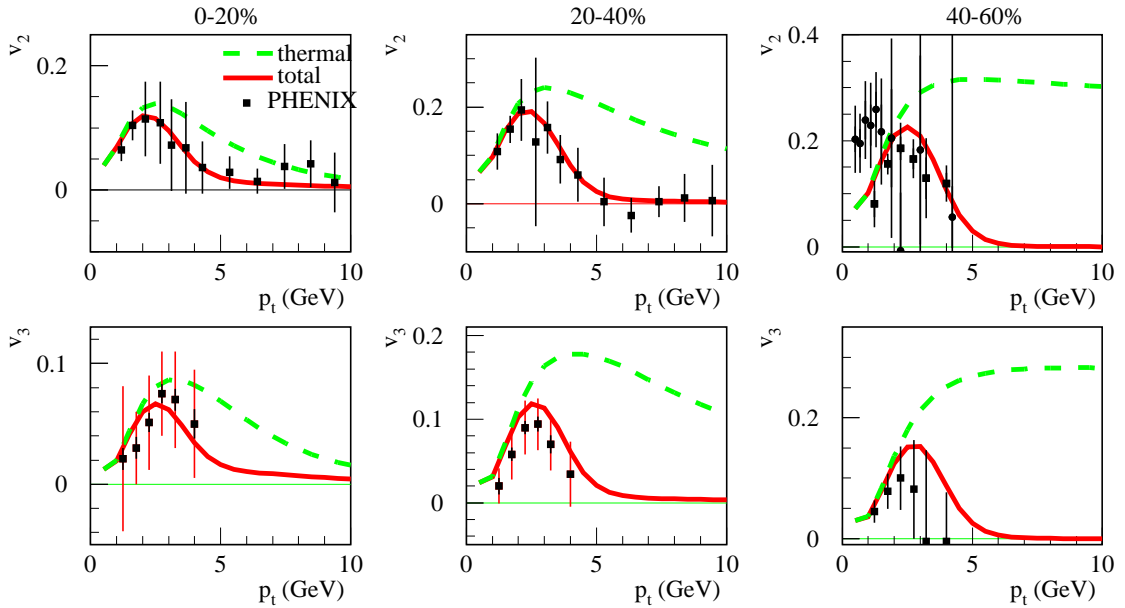


Figure 2: (Color Online) Elliptic flow v_2 (upper panels) and triangular flow v_3 (lower panels) of direct photons (solid lines) and thermal photons (dashed lines) from AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV for centrality 0-20%, 20-40% and 40-60% (from left to right). Data points v_2 and v_3 of direct photons from PHENIX [15].

The first thing we compare is the temperature evolution at the center point $(x,y,z)=(0,0,0)$ of the created hot dense matter in AuAu collisions at 200 GeV with centrality 40-60% in Fig. 4. The center temperature decreases with time in most EPOS3 events so that the event-averaged center temperature decrease with time. At the other hand, the event fluctuation allows a large variety. The center point is not always the hottest point of the system and it may be heated by the nearby hot spots, thus an increase of temperature appears in some events. An evident flat region appears in Hirano's results, because the equation of states are based on a first-order phase transition. This makes the transition region around $T_{pc}=170$ MeV as a key source of thermal photon

emission, as mentioned in [23]. EPOS3 shares this key temperature source of photon emission because the event-averaged temperature differs not much from Hirano's.

In the follow we investigate the evolution of eccentricity. The space eccentricity causes azimuthal anisotropies in transverse pressure gradients. The momentum eccentricity provides a picture of the dynamic build up of the elliptic flow of bulk hadrons and thermal photons. In Hirano's case, the second order event plane $\Phi_2 = 0$. Thus the definition of space eccentricity and momentum eccentricity at the second order are

$$\epsilon_r = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}, \quad (5)$$

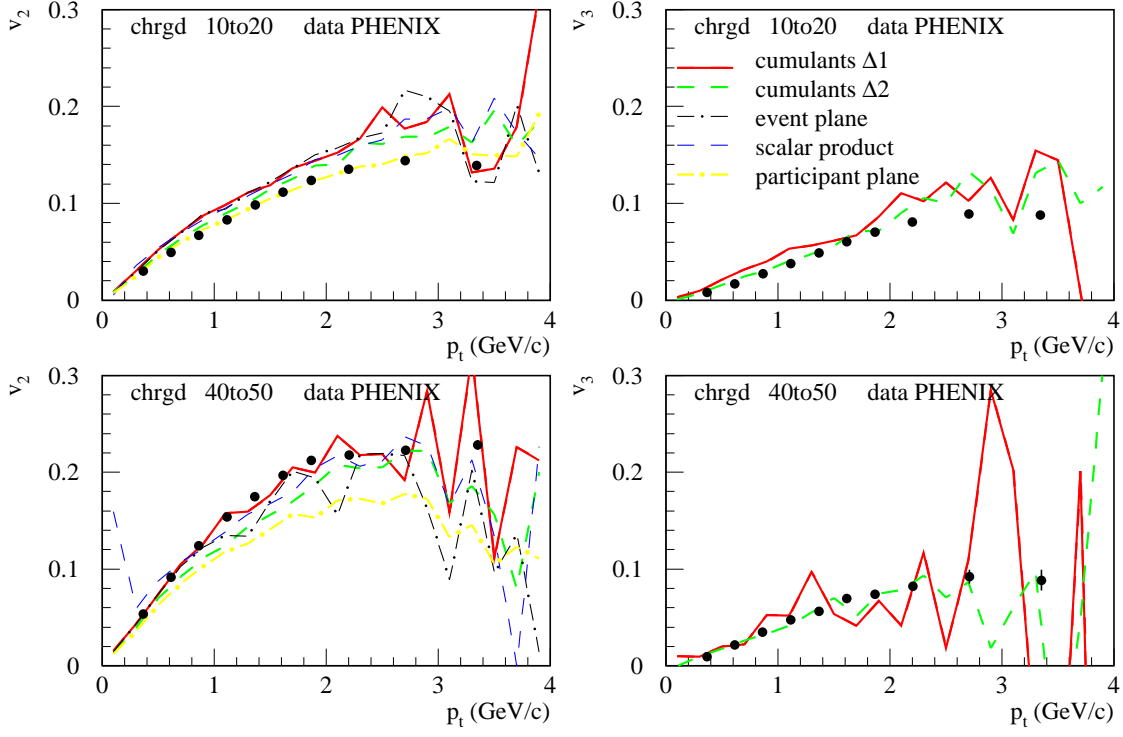


Figure 3: (Color Online) Elliptic flow v_2 (left panels) and triangular flow v_3 (right panels) of charged hadrons from AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV for centrality 10-20% (left) and 40-50% (right). Data points from PHENIX [14].

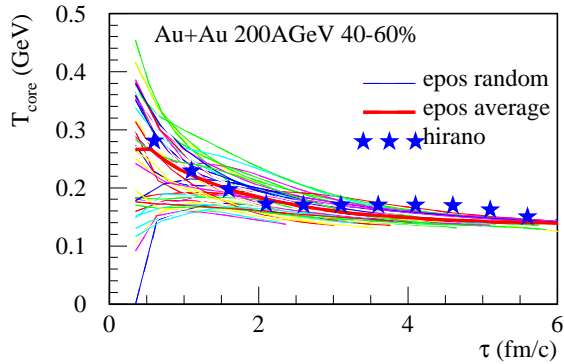


Figure 4: (Color Online) The time evolution of the temperature at the center point $(x,y,z)=(0,0,0)$ in AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV with centrality 40-60%. Thin lines stand for 50 random EPOS3 events. Thick line is the average of 2000 EPOS3 events. Stars for Hirano's hydrodynamics [10].

$$\epsilon_p = \frac{\langle T^{xx} - T^{yy} \rangle}{\langle T^{xx} + T^{yy} \rangle}. \quad (6)$$

Here $\langle \dots \rangle$ stands for an energy density weighted space integral.

The generalized space eccentricity of order n is

$$\epsilon_{r,n} e^{in\Phi_{r,n}} = \frac{\langle r^n e^{in\phi} \rangle}{\langle r^n \rangle}. \quad (7)$$

Motivated by this generalized space eccentricity, we also generalize the definition of the momentum eccentricity of order n as

$$\epsilon_{p,n} e^{in\Phi_{p,n}} = \frac{\langle v^n e^{in\phi_v} \rangle}{\langle v^n \rangle}. \quad (8)$$

Setting $\Phi_{p,2} = 0$ and vanishing viscous coefficients, then substituting $T^{\mu\nu} = (e + p)u^\mu u^\nu - g^{\mu\nu}p$, we see a coincidence between the two definitions of momentum eccentricity ϵ_p at order 2.

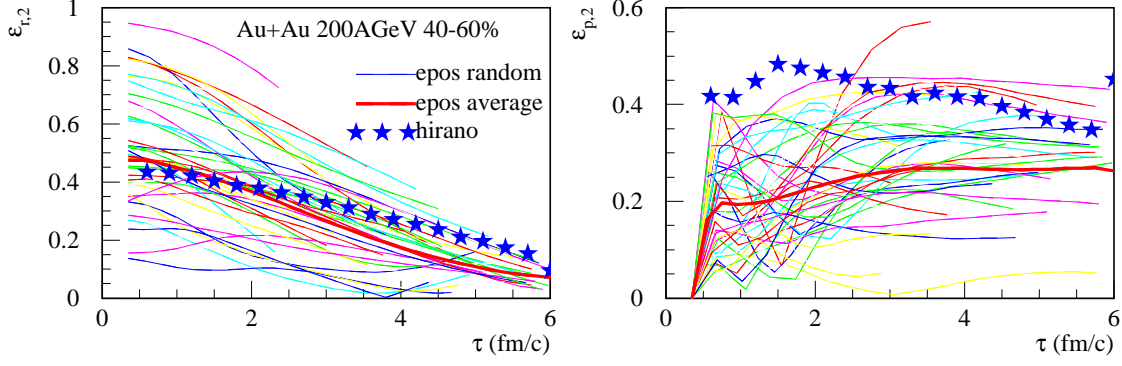


Figure 5: (Color Online) Second order eccentricity evolution with time. Left: space eccentricity $\epsilon_{r,2}$. Right: momentum eccentricity $\epsilon_{p,2}$. Same notation as Fig. 4.

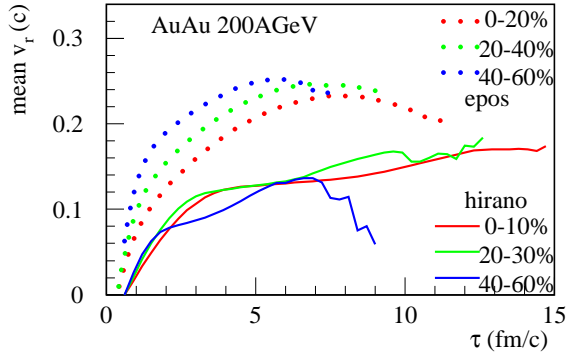


Figure 6: (Color Online) The difference between AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV for different centrality.

In Fig. 5 is shown the time evolution of the second order space eccentricity $\epsilon_{r,2}$ (left panel) and momentum eccentricity $\epsilon_{p,2}$ (right panel) for AuAu collisions at 200GeV with centrality 40-60%. Though the magnitude of space eccentricity and the life span in EPOS3 show a strong event fluctuation, the event-averaged $\epsilon_{r,2}$ is quite close to Hirano's. This is not surprise, because the two models use the same range of impact parameter b for each centrality class and the Wood-Saxon nuclear density works for both models. And this ensures both models reproduced the measured particle yields.

In the right panel of Fig. 5, however, the averaged momentum eccentricity in EPOS does not coincide with Hirano's hydro any more. It is much lower than Hirano's. As we investigated in [22], there is a good correspondence between the elliptic flow of thermal photons and hydro eccentricity $\epsilon_{p,2}$, where not $\epsilon_{p,2}$ but a similar quantity v_2^H was defined. Usually a larger $\epsilon_{p,2}$ obtained from more peripheral collisions makes a larger elliptic flow of produced particles, in a given hydro model. So a natural question is posed: How can both models explain the same hadrons' elliptic flow, with such a big difference in $\epsilon_{p,2}$? The answer will come soon in what follows.

The third order eccentricity is presented in Fig. 7. The melted color tubes of EPOS3 randomly distribute in the space, which make the space eccentricity $\epsilon_{r,3}$, large or small. As a consequence, flow velocity may carry large or small triangular symmetry and show up as the third order momentum eccentricity $\epsilon_{p,3}$. EPOS 3 provides relatively large $\epsilon_{r,3}$ and $\epsilon_{p,3}$ on average, while Hirano's regular initial condition makes both $\epsilon_{r,3}$ and $\epsilon_{p,3}$ vanished. Therefore hadrons or photons produced in Hirano's model carry a vanishing triangular flow v_3 .

One may notice that $\epsilon_{p,2}$ and $\epsilon_{p,3}$ from AuAu collisions at 40-60% are of the same magnitude on average. This looks strange because the produced hadrons and photons carry smaller v_3 than v_2 . In fact, both the eccentricity magnitude $\epsilon_{p,n}$ and the eccentricity direction $\Phi_{p,n}$ play an important role. We don't have initial flow velocity, and $\Phi_{p,2}$ has no definition at τ_0 . But with the expansion, $\Phi_{p,2}$ is either 0 or π , along x-axis, for all EPOS3 events. So the distribution of $\Phi_{p,2}$ is more like a δ -function. This δ -function $\Phi_{p,2}$ distribution keeps with the time evolution, till the end of the emission of photons and hadrons. The distribution of $\Phi_{p,3}$ have peaks at some angles such as $\pi/3$, $2\pi/3$ and 0, however, the peak are not sharp, with a relatively high stylobate. And moreover the peaks appear only for a short time around 2fm/c and disappear when $\tau > 4$ fm/c. The swinging of Φ_3 direction among events makes the triangular flow v_3 smaller than elliptic flow v_2 .

Now the question is, how can EPOS3 and Hirano's both explain hadronic elliptic flow, with so different second order momentum eccentricities? We investigate the mean radial flow in both models. The mean radial flow is defined as energy density weighted space integral of the radial flow

$$\langle v_r \rangle = \frac{\int \epsilon \sqrt{v_x^2 + v_y^2} d^3x}{\int \epsilon d^3x}, \quad (9)$$

where energy density ϵ and flow velocity v_x, v_y are functions of time and space coordinates. For EPOS3, additional event average is also included.

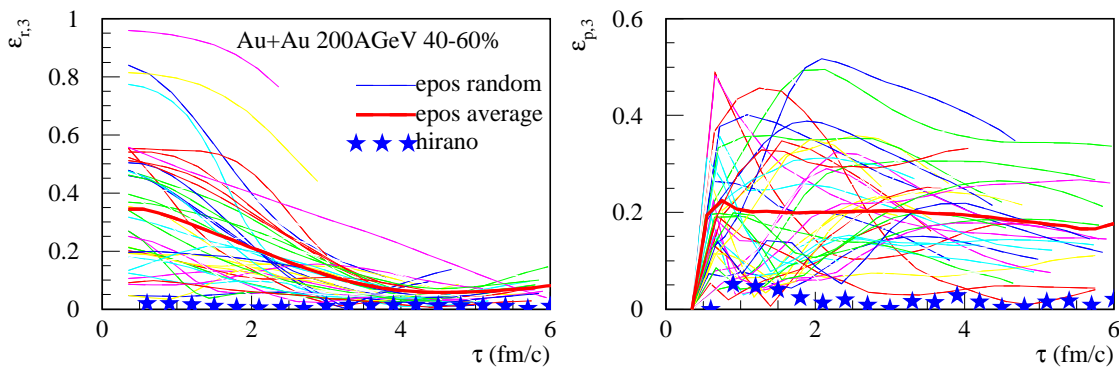


Figure 7: (Color Online) The third order eccentricity evolution with time. Left: space eccentricity $\epsilon_{r,3}$. Right: momentum eccentricity $\epsilon_{p,3}$. Same notation as Fig. 4.

In Fig. 6 the mean radial flows of the two models are compared, where solid lines stand for Hirano's and dotted lines for EPOS3. In both models, the more central collision has a longer time evolution. In both models, initial flow velocity is zero. The radial flow develops and increases with time in both models. The largest mean radial flows do not depend on centrality very much in both models. However, the mean radial flow of EPOS3 is much larger, about a factor of 2 of Hirano's. This compensates the lower second order momentum eccentricity. A good interplay between radial flow and second order momentum eccentricity $\epsilon_{p,2}$ can make the same hadronic elliptic flow explained in both models.

However, different from the surface emission of hadrons, the overall emission of thermal photons is very sensitive to the radial flow. To illustrate this, we reduce EPOS 3 radial flow to its half, but remain the temperature and eccentricity the same. The resulted the transverse momentum, elliptic flow and triangular flow of thermal photons from AuAu collisions at $\sqrt{s_{NN}}=200$ GeV with 40-60% are plotted as solid lines in Fig. 8, from left to right panels, where the dashed lines stand for normal EPOS results, c.f. Fig. 2 with centrality 40-60%. With the 50% radial flow, the spectrum is little modified. But the elliptic flow v_2 and triangular flow v_3 of thermal photons are strongly suppressed! Thus the strong radial in EPOS does build up a big elliptic flow and triangular flow of direct photons. Similar check is also done for hadrons, but much less effect.

The other question may be the system size of EPOS3 with such a big mean radial flow. We integrated the effective volume, which means the space with energy density higher than $0.08\text{GeV}/\text{fm}^3$ is counted. Compared to Hirano's system, the effective volume of EPOS3 is reduced about 30%. While Hirano's hydro provides a continuous example where the outer is the colder, EPOS3 provides a discrete system where cold holes may appear inside the hot bath with space fluctuations.

IV. CONCLUSIONS AND DISCUSSION

In this paper we investigated the large photon v_2 puzzle with EPOS3, a model which can explain the hadron production such as rapidity distribution, transverse momentum spectra, elliptic flow and triangular flow of identified/charged hadrons. Our calculated transverse momentum spectra, elliptic flow and triangular flow of direct photons coincide with the measured data. This is to say, we obtained a new solution to the large photon v_2 puzzle, other than delayed QGP formation or nonzero initial flow.

To understand what builds up such a big photon elliptic flow in EPOS3, we compared the system evolution with our previously investigated Hirano's (3+1)dimensional hydro model, which has got a similar elliptic flow of photons as other groups.

We found that a large event fluctuation in EPOS3. Yet, the event-averaged second order space eccentricity coincides with Hirano's, so that both models can provide particle yields properly. With the interplay between radial flow and second momentum eccentricity $\epsilon_{p,2}$, both models can explain hadronic elliptic flow. However, the radial flow seems to have a very strong effect on the overall emitted thermal photons than the surface emitted hadrons. With the same eccentricities and temperature, a doubled radial flow can increase thermal photons' v_2 and v_3 a lot, more than a factor of 5! Thus a good interplay between radial flow and eccentricity may provide a solution of the photon elliptic flow puzzle. The EPOS3 model has a bigger mean radial flow, yet a smaller effective volume, due to a discrete distribution of matter.

We generalize the definition of momentum eccentricities and find both the magnitude ϵ and direction Φ are important. The direction distribution makes a big difference between elliptic flow and triangular flow of produced particles.

Finally, we would like to know what exactly the direct photon puzzle implies, a gluon-rich matter or a discrete matter? We hope our mechanisms can be repeated by

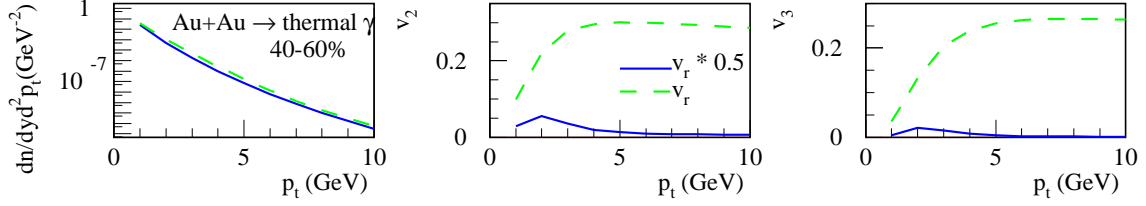


Figure 8: (Color Online) Effect of radial flow to thermal photons' transverse momentum spectrum, elliptic flow and triangular flow. The dashed lines are the EPOS normal results of AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV with 40-60%. Solid lines are the results with only half the radial flow.

other groups, and more realistic descriptions of the collision system can be obtained. As a prediction of this discrete matter, EPOS3 also provides a quite big elliptic flow of thermal dileptons[20], much bigger than current results obtained by other groups. We hope experimentalists will test with dilepton measurements.

Acknowledgments

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- [1] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **109**, 122302 (2012) [arXiv:1105.4126 [nucl-ex]].
 - [2] D. Lohner and f. t. A. Collaboration, arXiv:1212.3995 [hep-ex].
 - [3] H. van Hees, C. Gale and R. Rapp, Phys. Rev. C **84**, 054906 (2011) doi:10.1103/PhysRevC.84.054906 [arXiv:1108.2131 [hep-ph]].
 - [4] O. Linnyk, V. P. Konchakovski, W. Cassing and E. L. Bratkovskaya, Phys. Rev. C **88**, 034904 (2013) [arXiv:1304.7030 [nucl-th]].
 - [5] C. Shen, U. W. Heinz, J. F. Paquet, I. Kozlov and C. Gale, Phys. Rev. C **91**, no. 2, 024908 (2015) [arXiv:1308.2111 [nucl-th]].
 - [6] G. Basar, D. Kharzeev, D. Kharzeev and V. Skokov, Phys. Rev. Lett. **109**, 202303 (2012) [arXiv:1206.1334 [hep-ph]].
 - [7] B. Muller, S. Y. Wu and D. L. Yang, Phys. Rev. D **89**, no. 2, 026013 (2014) [arXiv:1308.6568 [hep-th]].
 - [8] F. M. Liu and S. X. Liu, Phys. Rev. C **89**, no. 3, 034906 (2014) [arXiv:1212.6587 [nucl-th]].
 - [9] F. M. Liu, arXiv:1305.5284 [hep-ph].
 - [10] T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, and Y. Nara, Phys. Lett. B **636**, 299 (2006); J. Phys. G **34**, S879 (2007); Phys. Rev. C **77**, 044909 (2008).
 - [11] P. Arnold, G. D. Moore, and L. G. Yaffe, J. High Energy Phys. **0111**, 057 (2001); J. High Energy Phys. **0112**, 9 (2001).
 - [12] S. Turbide, R. Rapp and C. Gale, Phys. Rev. C **69**, 014903 (2004) [hep-ph/0308085].
 - [13] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **104**, 132301 (2010) doi:10.1103/PhysRevLett.104.132301 [arXiv:0804.4168 [nucl-ex]].
 - [14] A. Adare *et al.* [PHENIX Collaboration], Phys. Rev. Lett. **107**, 252301 (2011) doi:10.1103/PhysRevLett.107.252301 [arXiv:1105.3928 [nucl-ex]].
 - [15] B. Bannier [PHENIX Collaboration], Nucl. Phys. A **931**, 1189 (2014) doi:10.1016/j.nuclphysa.2014.08.034 [arXiv:1408.0466 [nucl-ex]].
 - [16] K. Werner, B. Guiot, Iu. Karpenko, T. Pierog, arXiv:1312.1233, Phys.Rev. C **89** (2014) 6, 064903.
 - [17] K. Werner, Iu. Karpenko, T. Pierog, M. Bleicher, K. Mikhailov, arXiv:1004.0805, Phys.Rev. C **82** (2010) 044904.
 - [18] H.J. Drescher, M. Hladik, S. Ostapchenko, T. Pierog, K. Werner, hep-ph/0007198, Phys.Rept. **350** (2001) 93-289.
 - [19] M. Bleicher et al., J. Phys. G **25** (1999) 1859; H. Petersen, J. Steinheimer, G. Burau, M. Bleicher and H. Stocker, Phys. Rev. C **78** (2008) 044901.
 - [20] S. X. Liu, F. M. Liu, K. Werner and M. Yue, arXiv:1508.05160 [hep-ph].
 - [21] F. M. Liu, T. Hirano, K. Werner and Y. Zhu, Phys. Rev. C **79**, 014905 (2009) doi:10.1103/PhysRevC.79.014905 [arXiv:0807.4771 [hep-ph]].
 - [22] F. M. Liu, T. Hirano, K. Werner and Y. Zhu, Phys. Rev. C **80**, 034905 (2009) doi:10.1103/PhysRevC.80.034905 [arXiv:0902.1303 [hep-ph]].
 - [23] H. van Hees, M. He and R. Rapp, Nucl. Phys. A **933**, 256 (2015) doi:10.1016/j.nuclphysa.2014.09.009 [arXiv:1404.2846 [nucl-th]].